TIMES model for the Reunion Island: addressing reliability of electricity supply

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International Energy Workshop
Stockholm, June 21^{st} to 23^{rd} 2010

Abstract

The Reunion Island aims to have in 2030 an energy consumption based to 100% on renewable energy sources. In 2008, the total primary energy consumption was 1295 ktoe, and as most of small islands, the Reunion Island was highly dependent on fossil fuel imports (86.5%). This paper focuses on the target applied to the electricity sector, where the current use of renewable energy sources is 36%. To build plausible options for future energy systems, we rely on long-term planning models – such as the MARKAL/TIMES family of models. The MARKAL/TIMES models optimize energy systems in the long-term with an explicit bottom-up approach through a description of individual technologies. In this paper, we present the results obtained with a TIMES model dedicated to the supply and power sectors of the Reunion Island. We also tackle the technological and economical feasibilities of electricity systems provided by this model, considering in particular the incentives' system and the reliability of electricity supply.

Keywords: Long-term energy planning. Reunion Island. Reliability of electricity supply.

JEL: – Q4; O21; Q29 –

1 Introduction

The Reunion Island aims to have in 2030 an energy consumption based to 100% on renewable energy sources [1]. In 2008, the total primary energy consumption was 1295 ktoe, and as most of small islands, the Reunion Island was highly dependent on fossil fuel imports (86.5%). This paper focuses on the target applied to the electricity sector, where the current use of renewable energy sources is 36% [2]. Consequently the mix for electricity generation has to change substantially to reach the announced target. Fortunately, this change may be enabled by high potentials for renewable energy

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sources such as sugarcane bagasse, solar energy, wind energy, geothermal, or marine power.

However, achieving such a wide integration of renewable energy sources on power systems poses two main challenging problems to energy planners:

1. Energy policies should be designed to promote efficiently their development, knowing that electricity market designs and appropriate levels of incentives and subsidies are already difficult issues to deal with for small and isolated electricity systems [3, 4].

2. The technological feasibility and the associated cost of the integration of renewable energy sources on power systems are not adequately assessed. Indeed, the reliability of electricity supply, characterizing the ability of the electric system to withstand sudden disturbances [5, 6], should be addressed. In particular, high shares of renewable energy sources may strongly modify the reliability of supply.

These issues highlight the need for assessing the future options for the electricity sector in the Reunion Island. The MARKAL/TIMES type of models provide a partial solution to this need [7, 8, 9]: they are technology-rich, long-term, partial-equilibrium models and are useful to analyze investment alternatives and future plausible developments of energy systems in the mid- to long-term.

In this study, we develop a TIMES model dedicated to the Reunion Island (section 2) and present results obtained with this model to meet the target of 100% of renewable electricity production in 2030 (section 3). Finally, in a concluding section we discuss the feasibility of such a target by focusing on both economical and technological parameters of the electricity sector (section 4).

2 Model development

2.1 Assessment methodology

The study relies on a TIMES model dedicated to the Reunion Island which represents the latest evolution of the MARKAL (Market Allocation) family of models. The MARKAL/TIMES approach optimizes energy system in the long-term with an explicit bottom-up approach through a description of individual technologies by explicit input/output relationships. The main decision variables are investments levels, activity levels and total installed capacities. A synthetic description of the referece energy system covering the whole energy chain is given in figure 1.

In this work, the TIMES-Reunion model developed herein focuses on the supply and power sectors only, representing electricity demand growth in a simple summary fashion as a single demand. This design allows evaluation of power sector investment options againt a multiplicity of load growth, resource supply, and fuel price scenarios. The study covers the period 2008-2030.

In the following subsections, we describe the main components of the model.

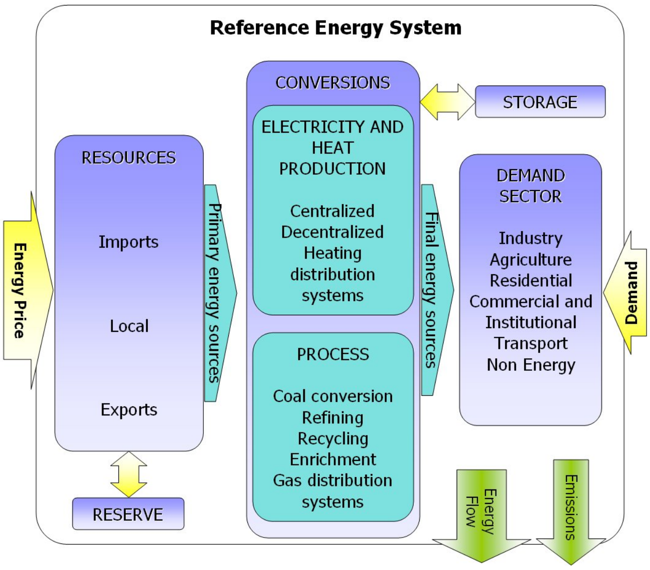


Figure 1: *Synthetic view of the Reference Energy System, issued from [10].*

Real terms (2008 prices)	Unit	2000	2008	2015	2020	2025	2030
OECD steam coal imports	\$2008/ton	41.22	120.59	91.05	104.16	107.12	109.4
IEA crude oil imports	\$2008/barrel	34.3	97.19	86.67	100.00	107.50	115.00
Heavy fuel oil	€2008/ton	-	196	174	201	216	231
Distillate fuel oil	€2008/hl	-	47	42	48	51	55

Table 1: *Fossil-fuel price assumptions [11].*

2.2 Resource supplies

The resources in the Reunion Island are domestic sugarcane bagasse and importations of coal, and fuel oils (heavy and distillate) as there are no refineries.

2.2.1 Imported fuel supplies

As a small market, the Reunion Island is a price taker on the international market. The energy market can be accurately modeled utilizing a single supply step with unlimited availability at a projected international market price. The fossil energy import prices are based on the projections of the World Energy Outlook [11]. We assume that fuel oil prices follow the projections of crude oil prices. Fossil-fuel price assumptions are listed in table 1.

2.2.2 Domestic sugarcane bagasse production

The Reunion Island produces around 10% of its annual electricity consumption with the combustion of the sugarcane bagasse. The highest value of electricity production with sugarcane bagasse was recorded in 2004 (292 GWh). The cost of the bagasse sugarcane is set to zero as the bagasse is a co-product of the sugar factories and that these factories are on the same production areas than the thermal power plants using

	Unit	2008	2010	2015	2020	2025	2030
Electricity consumption	GWh	2 546	2 710	3 110	3 500	3 805	4100
Growth rate	%	3.4	3.2	2.6	2.4	1.5	1.5
Power	MW	408	445	520	595	670	720

Table 2: *Electricity consumption growth in the Reunion Island from the medium scenario of EDF [2]. This scenario is extended from 2025 to 2030 with a growth rate of 1.5%.*

sugarcane bagasse. Electricity production from bagasse takes place in the power plants of Le Gol (111.5 MW) and Bois-Rouge (100 MW). These boilers also work with coal, thus producing electricity apart from the season of sugar production. due to steam use in the sugar factory [1].

2.3 Electricity demand

In 2008, the general features of the electricity sector in 2008 are the following [2, 12].

Electricity consumption rose up to 2546 GWh, divided into 50% coal, 14% other fossil fuels, 25% hydroelectricity, 10% sugarcane bagasse and 1% others.

The electricity peak demand was 408 MW.

The total installed capacities were slightly less than 650 MW.

Since 1995, the growth rate of electricity demand has decreased from 6.7% to 2.8%, and it is expected to continue decreasing and reach a value between 1 and 2% in 2025 [2]. Two forces for electricity consumption growth may explain the decrease: a decrease in the population[1] and economic growth. The economic growth decreases because the penetration rates of new end-uses, such as space cooling and consumer and business electronics, are already high. A projection for electricity consumption growth until 2025 was provided by Électricité de France (EDF) [2] (see table 2).

In this model, we haven't included time specification for electricity consumption yet. Load curves and peak demands are not described within this model. Thus, the modeled electricity system may require fewer power plants dedicated to peak loads than actually needed.

2.4 Existing power plants

Data for existing capacity, capacity factors, and efficiency are derived from reports on existing power plants by EDF and the Regional Agency for Energy in the Reunion Island (ARER) [2, 12]. Following discussion with experts, some of the technico-economical data have been revised to correspond more accurately to the electricity mix, in particular with the current spread of renewable energy sources.

Figure 2 provides an aggregate view of the residual capacity evolution used for the model. The figure only represents the lifespan of existing power plants and projects under construction.

[1]The current population is 795 000 and is expected to reach 1 000 030 in 2030.

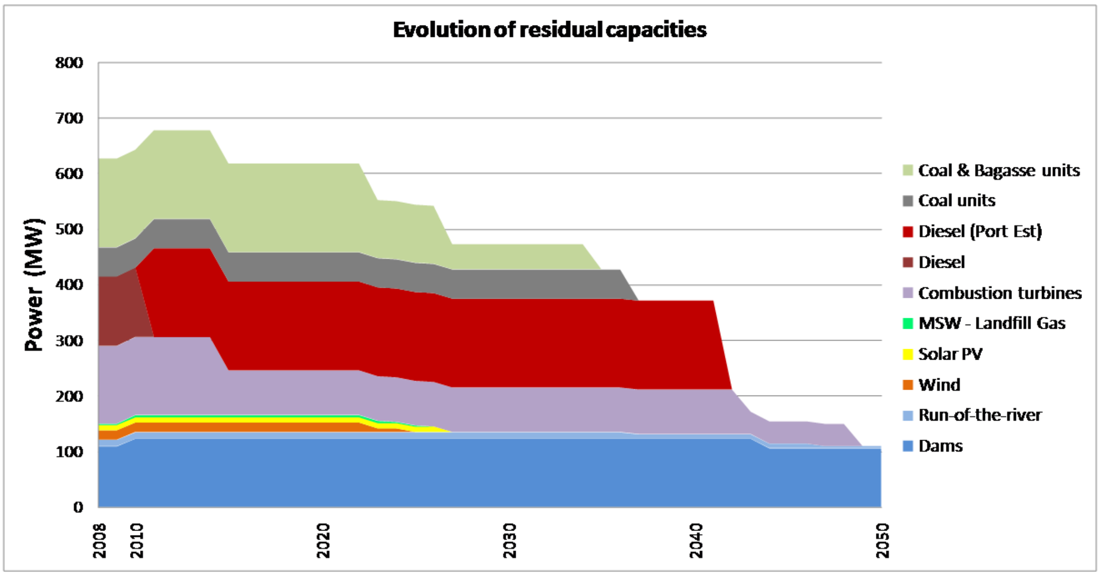


Figure 2: *Evolution of residual capacities.*

2.5 New power plant options and renewable potentials

Costs and performance characteristics of new power plants are derived from the database of the European RES2020[2] project. The 14 MW expansion of the dam of Rivière de l'Est is represented by a fix investment in 2009, as well as the 160 MW new heavy fuel oil plants at Le Port that is projected to be built.

According to experts and to quantitative and qualitative literature, the available renewable sources for the Reunion Island, and their technical and economic resource potential are as follows.

2.5.1 Biomass

For the past 40 years, the sugarcane industry has been reorganized and centralized: the number of sugar factories has decreased from 40 to 2 units, where the two remaining units have been built close to the thermal power plants of Le Gol (111.5 MW) and Bois-Rouge (100 MW).

For the past ten years, the production of sugarcane bagasse has fluctuated between 470 000 and 570 000 tons/year for a production of sugarcane slightly below 2 millions of tons. The total amount of cultivable land dedicated to sugarcane cultivation is 25 000 ha, accounting for 60% of the Reunion Island's cultivable land. However, the amount of land used for sugarcane has declined since 2004, due to a severe competition in land use with the rapid increase in urban spread. At present, the average sugarcane yield varies between 70 to 75 tons/ha. The yields are very heterogeneous due to different harvesting techniques and to disparities of the agronomical and climatic conditions.

[2]RES2020 is a European project which aims at monitoring and assessing the implementation of the directives on Renewable Energy Sources and the policy recommendations for 2020 in the EU-27. With this project, a number of future options for policies and measures are defined and studied with the use of TIMES.

	Unit	2000	2002	2004	2006	2008
Electricity production	GWh	261	241	292	273	263
Sugarcane	ktons	1 821	1 811	1 969	1 864	1 772
Surgarcane bagasse	ktons	565	539	561	524	510
Electricity production by ton of bagasse	MWh/ton	0.46	0.45	0.52	0.52	0.51
Ton of bagasse by ton of sugarcane		0.31	0.30	0.28	0.28	0.29

Table 3: *Electricity production from sugarcane bagasse [12].*

The amount of bagasse that remains at the mills after grinding and crushing of the sugarcane represents 110 tons/h out of 340 tons/h of sugarcane. The heat content of this amount of sugarcane bagasse provides 260 tons/h of medium pressure steam and generates 56 MWh of electricity. 42 MWh are transmitted to the power system of the Reunion Island, whereas only 9 MWh are used for the sugar refinery and 5 MWh for the power plant itself. The crushing season lasts from july to december and the amount of electricity produced with the sugarcane bagasse finally rises up to 260 GWh in average. Electricity production from sugarcane bagasse within the past ten years is exhibited in the table 3.

For the future, two sugarcane potential scenarios can be developed: one representing the current sugar industry with no major changes, except yields improvement, and one representing a sugarcane industry exclusively dedicated to the energy production. In both scenarios, research and development are made to develop new sugarcane species improving the average sugarcane yield and increasing the amount of bagasse issued from the sugarcane.

2.5.2 Hydropower

Until the 1980s, hydropower has been the main energy source in the Reunion Island. Interestingly, the electricity mix in 1982 has exclusively relied on hydroelectricity. The current hydropower capacity is 121 MW, 109.4 MW is produced from dams and 11.6 MW fom run-of-the-river capacities.

The remaining and currently undeveloped hydropower resource in the Reunion Island has been estimated at 147 MW, 26 MW from pump storage capacities and 121 MW from new hydropower plants [13]. These potential installations would correspond to the actual level of hydropower capacities.

Howeveer, considering environmental constraints due to the National Park, only a project of 56 MW in Takamaka has been declared feasible in the mid-term. It seems that keeping the boundaries of the National Park and increasing hydroelectricity production in order to reach the target of 100% of renewable electricity sources are incompatible objectives. Though, in the future, the limit set at 56 MW may be subject to discussions.

2.5.3 Wind

In 2008, wind power on the Reunion Island has reached 16.8 MW with two wind farms. Experts have estimated the wind potential at 50 MW.

2.5.4 Solar PV

The Reunion Island has excellent solar resources which are exploited with the use of solar photovoltaics and of thermal solar panels. At the end of 2008, electricity capacities reached 6.4 MW for solar farms and 3.6 MW for distributed solar PV. In remote areas close to the volcano, some other distributed solar PV are used off-grid.

Photovoltaics benefit from appealing policy mechanisms to encourage their development. Consequently, PV capacities may have a high growth rate. However, for grid stability reasons, the French government put a legal limit of 30% on the level of intermittent capacities of its overseas territories (decree of April, 23th 2008), including the Reunion Island. According to the system operator EDF, this will limit the spread of photovoltaics to roughly 160 MW.

2.5.5 Marine renewable energy

Two main projects using marine renewable energy are currently studied:

- A prototype of 1 MW Ocean Thermal Energy Conversion (OTEC) project. The technology uses the temperature difference that exists between deep and shallow waters to run a heat engine. In [1], the potential of Ocean Thermal Energy is valued at 10 MW in 2020 and 100 MW in 2030.

- A series of Pelamis wave energy converters. The Pelamis is a unique system to generate renewable electicity from ocean waves, and aims at reaching 30 MW offshore production by 2014.

2.5.6 Geothermy

Despite the presence of the volcano, the potential for geothermal power is not yet accurately estimated. The inhabitants do not accept the development of such projects. However, if things change, it is plausible to reach 30 MW of geothermal power in 2030.

2.5.7 Storage capacities

Finally, the island promotes the integration of storage capacities on its power system in order to manage more efficiently the intermittent sources. Two examples are the installation in 2009 of a 1 MW NaS battery, and the two call-for-tenders issued by the Commission de Régulation de l'Énergie[3] (CRE) for a total amount of 10 MW renewable energy farms with storage units.

2.6 Scenarios specification

As this work is still on-going we present in this paper the first results obtained. Further developments are needed to improve the accuracy of the results.

Various scenarios are investigated wherein the electricity system is required to simultaneously meet a given level of electricity demand (table 2) and reach the 2030

[3] The independent administrative body in charge of regulating the French electricity and gas markets

target with an electricity consumption based to 100% on renewable energy sources.

Consequenlty, height scenarios are built around three main assuptions concerning levels of fossil fuels imports, electricity demand, and sugarcane bagasse potential:

- An upper limit for the fossil fuels imports is set in 2008 and linearly decreased to 0 in 2030. The objective is to study the evolution of the electricity production in order to achieve an electricity system without fossil fuels. We also propose an alternative scenario with a softened constraint, where the limiting only coal imports. These scenarios are compared with a business-as-usual where no limits are set on the importations.
- We also consider scenarios with lower electricity consumption in order to study how lowering the demand helps to achieve the target of 100% of renewable energy sources.
- For all these scenarios, we set the potential for the renewable energy sources at the maximum rates described previously, except for sugarcane bagasse. In a first step, we only consider improvements of the current potential. Secondly, the option where the sugarcane industry is dedicated to energy production without sugar production is studied in the last series of scenarios (UpBAG) with an higher available potential.

The height scenarios are summarized in the table 4:

	Limit on imports			**Sugarcane Bagasse**
Demand	No limit	Limit on coal	Limit on all fuels	Higher potential
Standard	MedDEM	MedDEM_NoCOA	MedDEM_NoFOS	MedDEM_NoFOS_UpBAG
Low	LowDEM	LowDEM_NoCOA	LowDEM_NoFOS	LowDEM_NoFOS_UpBAG

Table 4: *Scenarios specification. The scenarios are built around three main assuptions concerning electricity demand, fossil fuel imports and sugarcane bagasse potential.*

The scenario MedDEM corresponds to the business-as-usual scenario.

3 Results

3.1 Calibration of the 2008 electricity production shares

In table 5, we compare the 2008 electricity production given by the model with actual data [2] and the similarity of the results is encouraging. In particular, the proportion between production based on fossil fuels and production based on renewable sources are the same.

The main difference concerns the production based on fossil fuels. With the model, coal participates to a higher share of electricity production. This can be explained by the fact that this TIMES-Reunion model does not include time specification for electricity consumption. Load curves and peak demands are not described within this model. Thus, the modeled electricity system requires in a lesser extent power plants dedicated to peak loads such as fuel oil turbines.

Energy sources	**Model (%)**	**EDF (%)**
Coal	56.90	50.55
Fuel Oils *(Distillate and Heavy)*	9.06	13.30
Sugarcane bagasse	10.21	10.31
Hydroelectricity	21.71	24.86
Wind energy	1.19	0.53
Solar energy	0.41	0.42
Municipal waste	0.52	0.03
Production	2 547 GWh	2 546 GWh

Table 5: *The 2008 electricity shares given by the TIMES-Reunion model compared to the actual values of EDF [2].*

3.2 Towards an energy consumption based to 100% on renewable energy sources

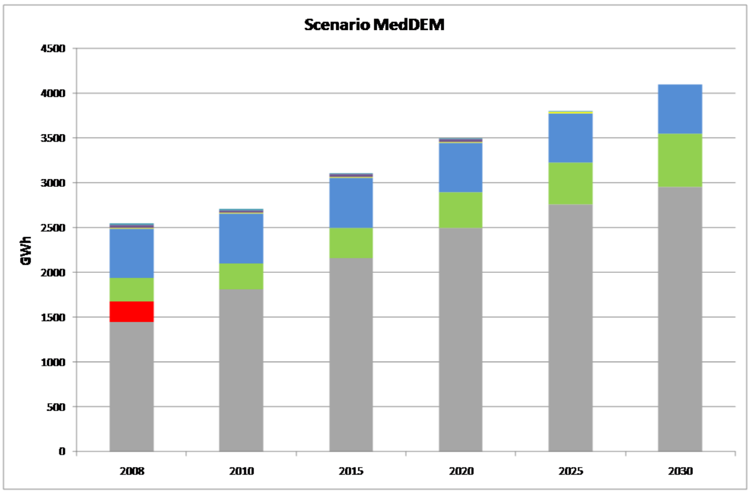
We now present the evolution of the electricity mix when the limitation of coal or all fossil fuel imports is set on the standard level of electricity demand. In the business as usual scenario (figure 3(a)), the actual shares of production roughly follow the increase in the demand.

However, there is no development of renewable energy sources despite their potentials. This is explained by the cost of power plants relying on these sources, compared to those relying on coal. Thus, the model can be improved by a precise description of the incentives' system favoring renewable energy sources or by modeling a constraint on the CO_2 emissions in the Reunion Island.

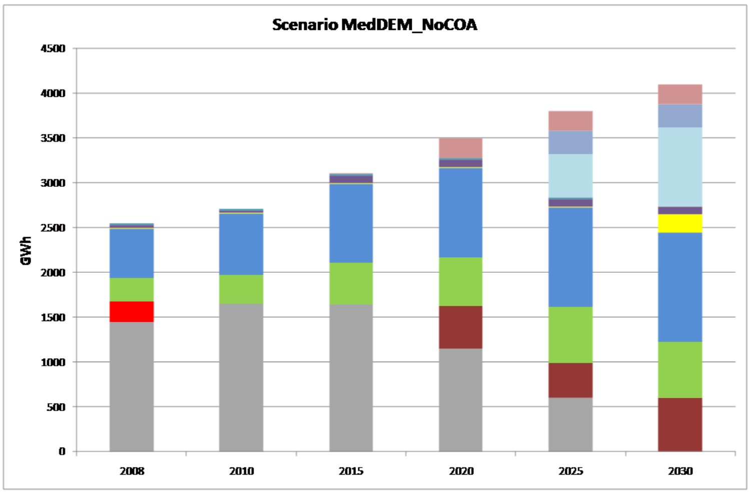
Furthermore, in this scenario, power plants based on fuel oils are hardly used, which emphasizes the need to represent the time characteristics and the load curves of the electricity demand in further developments.

The two other scenarios (figures 3(b) and 3(c)) show that there is a large room for the development of renewable energy sources when a constraint is set on coal or on all fossil fuels import. In both scenarios, new renewable energy sources appear such as geothermy, ocean thermal energy, or wave energy. Besides, hydroelectricity increases sharply.

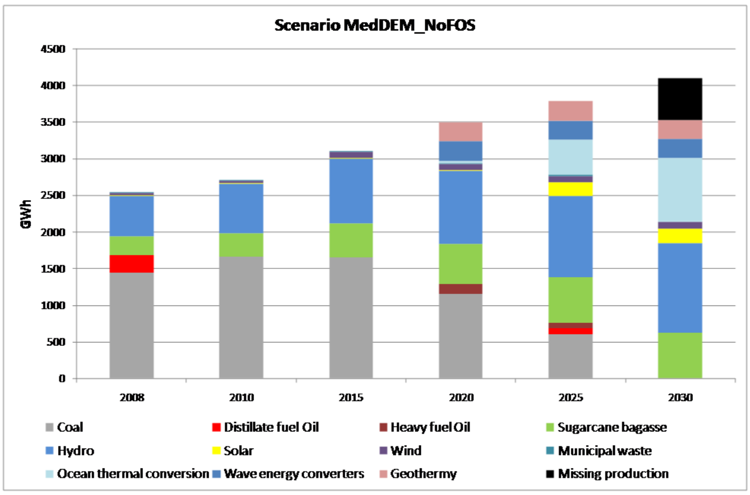
With the constraint on both coal and petroleum products, the figure 3(c) shows that around 500 GWh of electricity demand can not be met in 2030. This remark leads to the following subsection, where we focus on the electricity mix with a lower electricity demand.



(a) Business as Usual.



(b) Without importation of coal in 2030.



(c) Without importation of fossil fuels in 2030.

Figure 3: *Shares of the electricity production for the electricity demand proposed in the table 2. The importations of coal and petroleum products are constrained over the time horizon: from their levels in 2008 to 0 in 2030.*

3.3 Lower growth of the electricity demand

The decrease in the electricity demand may be due to two main features: a slower growth rate of the demand, or deep improvements of energy efficiency of end-use devices. If electricity consumption goes in this direction, it will consequently ease the Reunion Island to reach its ambitious target of 100% of renewable energy sources by 2030.

The lower electricity demand is given in the table 6 and the figure 4 presents the changes it induces on the electricity mix.

	Unit	2008	2010	2015	2020	2025	2030
Electricity consumption	GWh	2 546	2 700	3 030	3 325	3 545	3725
Growth rate	%	3.4	3.0	2.1	1.9	1	1
Power	MW	408	430	485	540	595	625

Table 6: *Electricity consumption growth in the Reunion Island from the lower scenario of EDF [2]. This scenario is extended from 2025 to 2030 with a growth rate of 1%.*

The trends are similar to those of the figure 3. As expected, the amount of missing electricity in the scenario LowDEM_NoFOS is reduced to around 200 GWh (figure 4(c)). Besides, the amount of fuel oils used decreases when the constraint is only set on the coal imports (figure 4(b)).

3.4 Higher potential for sugarcane bagasse production

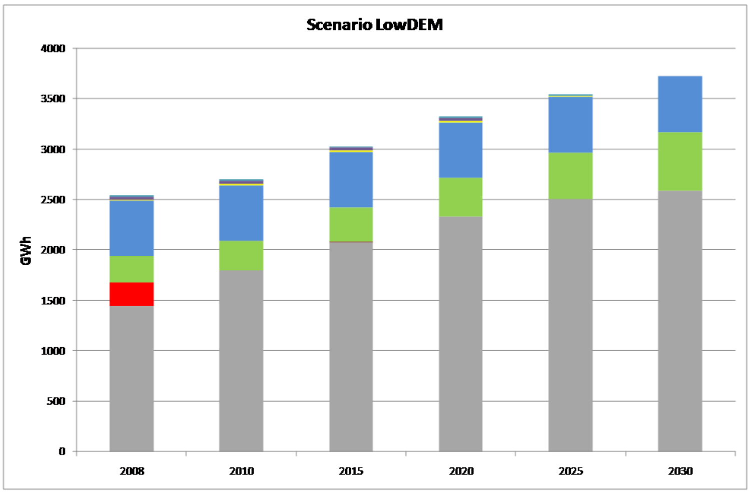
In this section, we consider a radical change of the sugarcane industry, where sugarcane production is only dedicated to electricity production, as suggested in [1]. In this case, the available potential of sugarcane bagasse is increased as the whole sugarcane is used for energy purposes.

The figure 5 shows the subsequent evolutions of electricity shares. Interestingly, it seems that the whole available potentials for renewable energy sources can meet the lower electricity demand (figure 5(b)). However, this result may be discussed with caution, as the work presented in this paper is still on-going. Further developments are expected in order to improve the robustness of the results. Nevertheless, these first results are very promising and encourage to study more deeply the electricity system of the Reunion Island.

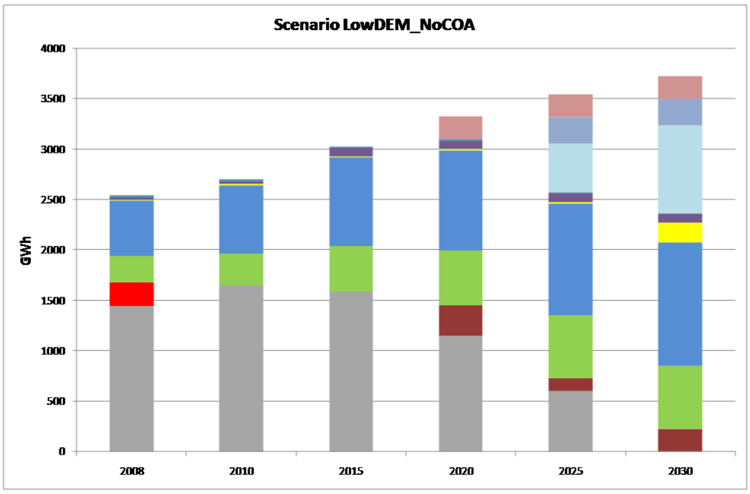
4 Conclusive discussion

In this paper, we have presented the development and the first results of the TIMES-Reunion model, for which results concerning the spread of renewable energy sources is discussed around three main assumptions. Height scenarios have been built around these assuptions concerning levels of fossil fuels imports, electricity demand, and sugarcane bagasse potentials.

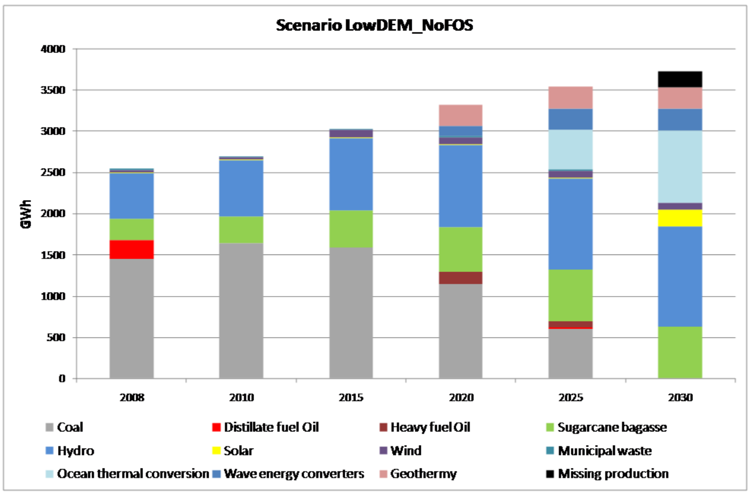
Furthermore, the promising results obtained encourage to study more deeply the electricity system of the Reunion Island. In particular, we want to pay attention to the



(a) Business as Usual (lower electricity demand).

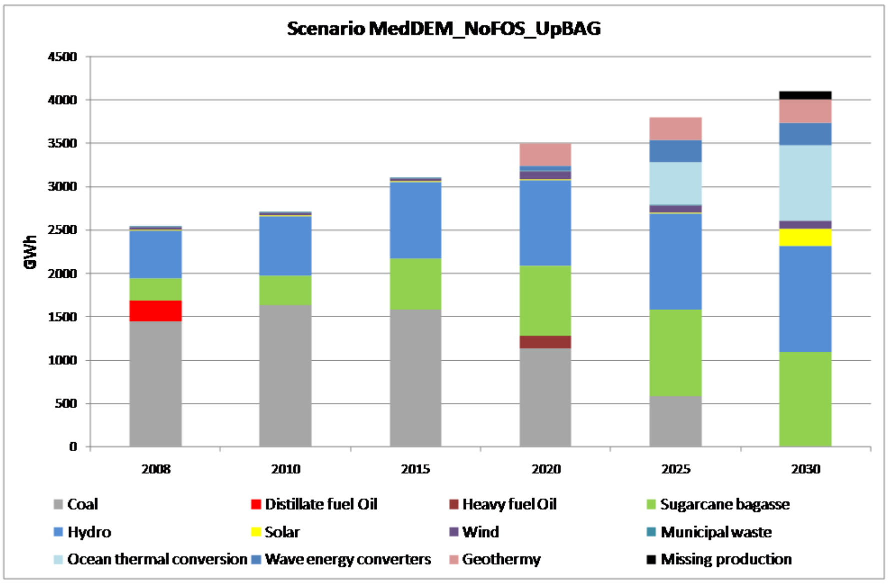


(b) Without importation of coal in 2030.

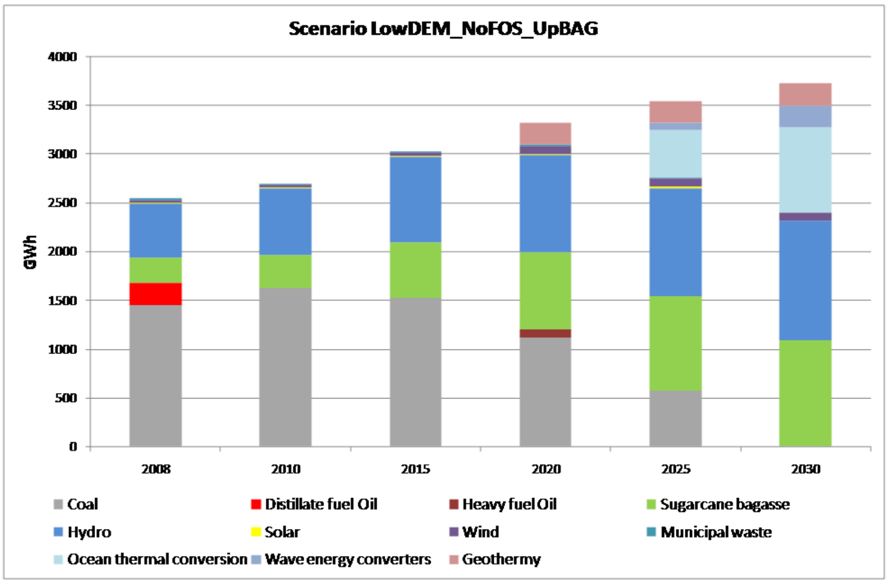


(c) Without importation of fossil fuels in 2030.

Figure 4: *Shares of the electricity production for a lower electricity (see table 6 according to EDF [2]).*



(a) Standard electricity demand.



(b) Lower electricity demand.

Figure 5: *Shares of the electricity production assuming that the sugarcane industry will be dedicated to energy production in the medium-term (according to [1]) and without fossil fuels importations in 2030.*

technological and economical feasibility of the long-term electricity system. In further developements, we also want to consider both economical and technological feasibility in long-term planning exercises, described as follow:

4.1 Describing the incentives' system

An extension of the TIMES-Reunion model may be proposed to study precisely the incentives' system for the spread of renewable energy sources which is well-developed on the Reunion Island. As an oversea territory, the electricity sector of the Reunion Island strongly relies on subsidies to balance out its geographical situation compared to Metropilitan France. These subsidies are preferentially devoted to renewable energy sources. In particular, photovoltaïcs, and in a lesser extent sugarcane bagasse, currently benefits from appealing policy mechanisms that encourage their development. But other renewable energy sources are also incentivized but neither their remaining potential can be easily valued nor the policy mechanisms are sufficiently attractive. Results concerning the spread of renewable energy sources will gain in accyracy and robustness when taking such mechanisms into account.

4.2 Focusing on the reliability of electricity supply

The technological feasibility of electricity systems is also a crucial issue in order to improve results provided in long-term exercises. Indeed, high shares of renewable – and in particular intermittent – energy sources in power systems may induce a decrease of reliability of electricity supply. Thus, restoring an appropriate level of reliability on power systems requires additional investments and extra-losses, which add to the assumed total cost of future power systems.

According to the UCTE handbook [6], the reliability of an electric system is twofold. On the one hand, it is the ability to supply the electrical demand and energy requirements at all times, taking into account scheduled and reasonably expected unscheduled outages. On the other hand, it is the capacity to handle load fluctuations such as electric short circuits and unanticipated loss of system elements.

To ensure these features, power systems rely on frequency and voltage management [14]. Frequency and voltage are crucial quantities, whose deviations can lead to power outages. This typically occurs when the system experiences transient states (e.g. lightning), or is recovering from production or load fluctuations.

Maintaining voltage and frequency between appropriate limits depends respectively on the reactive power of the system and on the kinetic and spinning reserves. This emphasizes the need for reactive power and for appropriate reserves levels on power systems.

Most renewable energy sources, and in particular intermittent ones, do not provide the required reserve levels as efficiently as conventional power units (for example thermal units and hydroelectricity) [15]. Furthermore, intermittent energy sources commonly induce frequent and higher magnitude production fluctuations further increasing the need for reliability of the electric system.

To assess the technicological feasibility of future power systems, the cost induced by reliability requirements should be considered. This cost may be provided by a method based on a thermodynamic approach applied to power systems [5, 16].

Furthermore, this work is a part of a larger project, which aims at integrating reliability requirements in prospective studies. Another aspect of the project focuses on the evaluation of the cost of reliability in future power systems.

Acknowledgment

This research was supported by the Chair Modeling for sustainable development, driven by MINES ParisTech, Ecole des Ponts ParisTech, AgroParisTech, and ParisTech; and supported by ADEME, EDF, RENAULT, SCHNEIDER ELECTRIC and TOTAL.

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